# Oil & Gas Manuscript: Supplemental Materials

*Overview of WRF Modeling*

Version 3.5 of the WRF model, Advanced Research WRF (ARW) core (Skamarock et al., 2008) was used for generating hourly 2011 meteorology. WRF was initialized with the 12km North American Model (12NAM) analysis product provided by National Climatic Data Center (NCDC). When the 12NAM data was not available, the 40 km Eta Data Assimilation System (EDAS) analysis (ds609.2) from the National Center for Atmospheric Research (NCAR) was used to fill these gaps. Physics options include Kain-Fritsch cumulus parameterization utilizing the moisture-advection trigger, Pleim-Xiu land surface model, Asymmetric Convective Model version 2 planetary boundary layer scheme, RRTMG longwave and shortwave radiation schemes, and Morrison double moment microphysics. The 'ipxwrf' program was used to initialize deep soil moisture at the start of the run using a 10-day spinup period (Gilliam and Pleim, 2010). Landuse and land cover data were based on the 2011 National Land Cover Database (NLCD 2011). Sea surface temperatures were ingested from the Group for High Resolution Sea Surface Temperatures (GHRSST) (Stammer et al., 2003) 1 km data product. Analysis nudging for moisture, winds, and temperature were applied above the boundary layer only.

*References*

Gilliam, R.C., Pleim, J.E., 2010. Performance assessment of new land surface and planetary boundary layer physics in the WRF-ARW. Journal of Applied Meteorology and Climatology 49, 760-774.


Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X., Wang, W., Powers, J.G., 2008. A description of the Advanced Reserch WRF version 3. NCAR Technical Note NCAR/TN-475+STR.


Stammer, D., Wentz, F., Gentemann, C., 2003. Validation of microwave sea surface temperature measurements for climate purposes. Journal of Climate 16, 73-87.

**Table S-1:** Epidemiological Study Parameters Used to Quantify $PM_{2.5}$-Attributable Risks

| Endpoint | Study | Study Population | Risk Estimate (95 Percent Confidence Interval)[A] |
|---|---|---|---|
| **Premature Mortality** | | | |
| Cohort study, all-cause | Krewski et al. (2009) | >29 years | RR = 1.06 (1.04 – 1.06) per 10 µg/m³ |
| | Lepeule et al. (2012) | >24 years | RR = 1.14 (1.07 – 1.22) per 10 µg/m³ |
| Time series, all-cause | Zanobetti and Schwartz (2009) | All ages | RR = 1.0098 (1.0075—1.022) |
| **Chronic Illness** | | | |
| Nonfatal heart attacks | Peters et al. (2001) | Adults (>18 years) | OR = 1.62 (1.13 – 2.34) per 20 µg/m³ |
| **Hospital & Emergency Department Admissions** | | | |
| Respiratory | Babin et al. (2007)—ICD 493 (asthma) | <19 | β=0.002 (0.004337) |
| | Moolgavkar (2000)—ICD 490–496 (COPD) | 18–64 years | 1.02 (1.01—1.03) per 36 µg/m³ |
| | Zanobetti and Schwartz (2006)—ICD 470-519 (All Respiratory) | >64 years | β=0.00207 (0.00446) |
| | Pooled estimate from random effects meta-analysis estimate | All ages | RR = 1.02 (1.00—1.04) |
| Cardiovascular | *Pooled using equal weights:* Zanobetti and Schwartz (2009)—ICD 390-459 (all cardiovascular) | >64 years | β=0.00189 (0.000283) |
| | Peng et al. (2009)—ICD 426-427; 428; 430-438; 410-414; 429; 440-449 (Cardio-, cerebro- and peripheral vacsular disease) | >64 years | β=0.00068 (0.000214) |
| | Peng et al. (2008)—ICD 426-427; 428; 430-438; 410-414; 429; 440-449 (Cardio-, cerebro- and peripheral vacsular disease) | >64 years | β=0.00071 (0.00013) |

| | | | |
|---|---|---|---|
| | Bell et al. (2008)—ICD 426-427; 428; 430-438; 410-414; 429; 440-449 (Cardio-, cerebro- and peripheral vacsular disease) | >64 years | |
| | Moolgavkar (2000)—ICD 390–429 (all cardiovascular) | 20–64 years | RR=1.04 (t statistic: 4.1) per 10 μg/m$^3$ |
| Asthma-related ER visits | Mar et al. (2004) | | RR = 1.04 (1.01 – 1.07) per 7 μg/m$^3$ |
| | Slaughter et al. (2003) | All Ages | RR = 1.03 (0.98 – 1.09) per 10 μg/m$^3$ |
| **Other Health Endpoints** | | | |
| Acute bronchitis | Dockery et al. (1996) | 8–12 years | OR = 1.50 (0.91 – 2.47) per 14.9 μg/m$^3$ |
| Upper respiratory symptoms | Pope et al. (1991) | Asthmatics, 9–11 years | 1.003 (1—1.006) per 10 μg/m$^3$ |
| Lower respiratory symptoms | Schwartz and Neas (2000) | 7–14 years | OR = 1.11 (1.58 – 1.58) per 15 μg/m$^3$ |
| Asthma exacerbations | Ostro et al. (2001) (cough, wheeze and shortness of breath) | 6–18 years | RR = 1.04 (1.01 – 1.07) per 7 μg/m$^3$ |
| | Mar et al. (2004) (cough, shortness of breath) | | RR = 1.03 (0.98 – 1.09) per 10 μg/m$^3$ |
| Work loss days | Ostro (1987) | 18–65 years | β=0.0046 (0.00036) |
| Minor Restricted Activity Days (MRADs) | Ostro and Rothschild (1989) | 18–65 years | β=0.00220 (0.000658) |

A Where available, relative risk (RR) and odds ratios (OR) are reported from each epidemiological study. Otherwise, beta coefficients and standard errors are reported from each study. Beta coefficients were derived from each RR or OR using the following equation: (LN(RR or OR))/unit change in pollution.

**Table S-2:** Epidemiological Study Parameters Used to Quantify Ozone-Attributable Risks

| Endpoint | Study | Study Population | Risk Estimate (95th Percentile Confidence Interval)[A] |
|---|---|---|---|
| **Premature Mortality** | | | |
| Time Series | Smith et al. (2009) | All Ages | $\beta$ = 0.00032 (0.00008) |
| | Zanobetti & Schwartz (2008) | All Ages | $\beta$ = 0.00051 (0.00012) |
| **Hospital & Emergency Department Admissions** | | | |
| Respiratory | Katsouyanni et al. (2009) | >65 | $\beta$ = 0.00064 (0.00040) |
| | Glad et al. (2012) | All Ages | $\beta$ = 0.00306 (0.00117) |
| | Ito et al. (2007) | >64 years | $\beta$ = 0.00521 (0.00091) |
| | Mar and Koenig (2010) | All ages | $\beta$ = 0.01044 (0.00436) (0-17 yr olds) $\beta$ = 0.00770 (0.00284) (18-99 yr olds) |
| Asthma ED visits | Peel et al. (2005) | All ages | $\beta$ = 0.00087 (0.00053) |
| | Sarnat et al. (2013) | All ages | $\beta$ = 0.00111 (0.00028) |
| | Wilson et al. (2005) | All ages | RR = 1.022 (0.996 – 1.049) |
| Asthma Exacerbation | Mortimer et al. (2002) | 6-18 | $\beta$ = 0.00929 (0.00387) |
| | Schildecrout et al. (2006) | 6-18 | $\beta$ = 0.00222 (0.00282) |
| School loss days | Chen et al. (2000) | 5-17 | $\beta$ = 0.015763 (0.004985) |
| | Gilliland et al. (2001) | 5-17 | $\beta$ = 0.007824 (0.004445) |
| Acute Respiratory Symptoms | Ostro and Rothschild | 18-65 | $\beta$ = 0.002596 (0.000776) |

*Procedure for projecting death rates to future years*

The BenMAP-CE program contains age- and cause-stratified death rates for each county in the contiguous U.S. through the year 2060 in 5-year increments. To estimate these rates, we calculated annual adjustment factors, based on a series of Census Bureau projected national mortality rates (for all- cause mortality), to adjust the age- and county-specific mortality rates calculated using an average of 2012-2014 data from the CDC-WONDER database as a baseline (Table S-1). We used the following procedure:

1. For each age group, we obtained the series of projected national mortality rates from 2013 to 2050 (see the 2013 rate in Table S-1 below) based on Census Bureau projected life tables.

2. We then calculated, separately for each age group, the ratio of Census Bureau national mortality rate in year Y (Y = 2014, 2015, …, 2060) to the 2013 rate. These ratios are shown for selected years in Table S-2.

3. Finally, to estimate mortality rates in year Y (Y = 2015, 2020, …, 2060) that are both age-group-specific and county-specific, we multiplied the county- and age-group-specific mortality rates for 2012-2014 by the appropriate ratio calculated in the previous step. For example, to estimate the projected mortality rate in 2015 among ages 18-24 in Wayne County, MI, we multiplied the mortality rate for ages 18-24 in Wayne County in 2012-2014 by the ratio of Census Bureau projected national mortality rate in 2015 for ages 18-24 to Census Bureau national mortality rate in 2013 for ages 18-24.

**Table S-3:** All-Cause Mortality Rate (per 100 people per year) by Source, Year and Age Group

| Source & Year | 18-24 | 25-34 | 35-44 | 45-54 | 55-64 | 65-74 | 75-84 | 85+ |
|---|---|---|---|---|---|---|---|---|
| Calculated CDC 2012-2014 | 0.078 | 0.107 | 0.173 | 0.405 | 0.862 | 1.797 | 4.628 | 13.580 |
| Census Bureau 2013[1] | 0.088 | 0.102 | 0.183 | 0.387 | 0.930 | 2.292 | 5.409 | 13.091 |

**Table S-4:** Ratio of Future Year All-Cause Mortality Rate to 2013 Estimated All-Cause Mortality Rate by Age Group

| Year | 18-24 | 25-34 | 35-44 | 45-54 | 55-64 | 65-74 | 75-84 | 85+ |
|---|---|---|---|---|---|---|---|---|
| 2015 | 0.96 | 1.02 | 0.96 | 0.96 | 1.01 | 1.02 | 1.03 | 1.00 |
| 2020 | 0.98 | 1.04 | 0.97 | 0.98 | 1.02 | 1.03 | 1.03 | 1.00 |
| 2025 | 0.74 | 0.80 | 0.75 | 0.77 | 0.85 | 0.91 | 0.93 | 0.97 |

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[1] For a detailed description of the model, the assumptions, and the data used to create Census Bureau projections, see the working paper, "Methodology and Assumptions for the 2012 National Projections," which is available on http://www.census.gov/population/projections/files/methodology/methodstatement12.pdf

**Table S-5:** Baseline and Prevalence Rates for Included Morbidity Endpoints

| Endpoint | Parameter | Rates | |
|---|---|---|---|
| | | Value | Source[a] |
| Hospitalizations | Daily hospitalization rate | Age-, region-, and cause-specific rate | Agency for Healthcare Research and Quality (2007) |
| Asthma ER Visits | Daily asthma ER visit rate | Age- and region-specific visit rate | Agency for Healthcare Research and Quality (2007) |
| Nonfatal Myocardial Infarction (heart attacks) | Daily nonfatal myocardial infarction incidence rate per person, 18+ | Age-, region-, state-, and county-specific rate | 2007 AHRQ data files; adjusted by 0.93 for probability of surviving after 28 days (Rosamond 1999) |
| Asthma Exacerbations | Incidence<br>• daily wheeze<br>• daily cough<br>• daily dyspnea | 0.173<br>0.145<br>0.074 | Ostro et al. (2001) |
| | Prevalence among asthmatic children | 0.0780 | American Lung Association (2010) |
| Acute Bronchitis | Annual bronchitis incidence rate, children | 0.043 | American Lung Association (2002) Table 11 |
| Lower Respiratory Symptoms | Daily lower respiratory symptom incidence among children[d] | 0.0012 | Schwartz (1994b, Table 2) |
| Upper Respiratory Symptoms | Daily upper respiratory symptom incidence among asthmatic children | 0.3419 | Pope et al. (1991, Table 2) |
| Work Loss Days | Daily WLD incidence rate per person (18–65)<br>• Aged 18–24<br>• Aged 25–44<br>• Aged 45–64 | 0.00540<br>0.00678<br>0.00492 | US Bureau of the Census (2001) |
| Minor Restricted-Activity Days | Daily MRAD incidence rate per person | 0.02137 | Ostro and Rothschild (1989) |

[a] Healthcare Cost and Utilization Program (HCUP) database contains individual level, state and regional-level hospital and emergency department discharges for a variety of ICD codes.

[b] See ftp://ftp.cdc.gov/pub/Health_Statistics/NCHS/Datasets/NHDS/.

[c] See ftp://ftp.cdc.gov/pub/Health_Statistics/NCHS/Datasets/NHAMCS/.

[d] Lower respiratory symptoms are defined as two or more of the following:  cough, chest pain, phlegm, and wheeze.

1 **Table S-6: PM$_{2.5}$ and Ozone Related Morbidity Outcomes Attributable**
2 **to the Oil and Gas Sector in 2025**

| Endpoint and Pollutant | Incidence (95% confidence interval)[A] |
|---|---|
| *Premature Mortality* | |
| PM$_{2.5}$-Related Premature Death, Ages 30-99 (Krewski et al. 2009) | 1,000 (670—1,300) |
| PM$_{2.5}$-Related Premature Death, Ages 25-99 (Lepeule et al. 2012) | 2,300 (1,100—3,400) |
| Ozone-Related Premature Death, Ages 0-99 (Smith et al. 2008) | 530 (260—800) |
| Ozone-Related Premature Death, Ages 0-99 (Zanobetti & Schwartz 2009) | 970 (520—1,400) |
| Respiratory Hospital Admissions, Ages 0-99 (PM$_{2.5}$ & O$_3$) | 1,100 (-280—2,300) |
| Cardiovascular Hospital Admissions, Ages 18-99 (PM$_{2.5}$) | 240 (110—440) |
| Acute Bronchitis, Ages 8-12 (PM$_{2.5}$) | 1,300 (-300—2,900) |
| Respiratory Emergency Room Visits, Ages 0-99 (PM$_{2.5}$ & O$_3$) | 3,600 (110—11,000) |
| Asthma Exacerbation, Ages 6-18 (PM$_{2.5}$ & O$_3$) | 1,100,000 (-900,000—2,600,000) |
| Work Loss Days, Ages 18-64 (PM$_{2.5}$) | 110,000 (94,000—130,000) |
| Acute Respiratory Symptoms, Ages 18-64 (PM$_{2.5}$ & O$_3$) | 3,000,000 (1,500,000—4,400,000) |
| Upper Respiratory Symptoms, Ages 9-11 (PM$_{2.5}$) | 23,000 (4,300—43,000) |
| Lower Respiratory Symptoms, Ages 7-14 (PM$_{2.5}$) | 16,000 (6,300—27,000) |
| Acute Myocardial Infarction, Ages 18-99 (PM$_{2.5}$) | 980 (240—1,700) |
| School Loss Days, Ages 5-17 (O$_3$) | 770,000 (270,000—1,700,000) |

[A] The confidence intervals for some endpoints were quantified by
sampling from a distribution that crosses the null; thus, some lower

confidence intervals are negative. Rather than setting these to zero, we
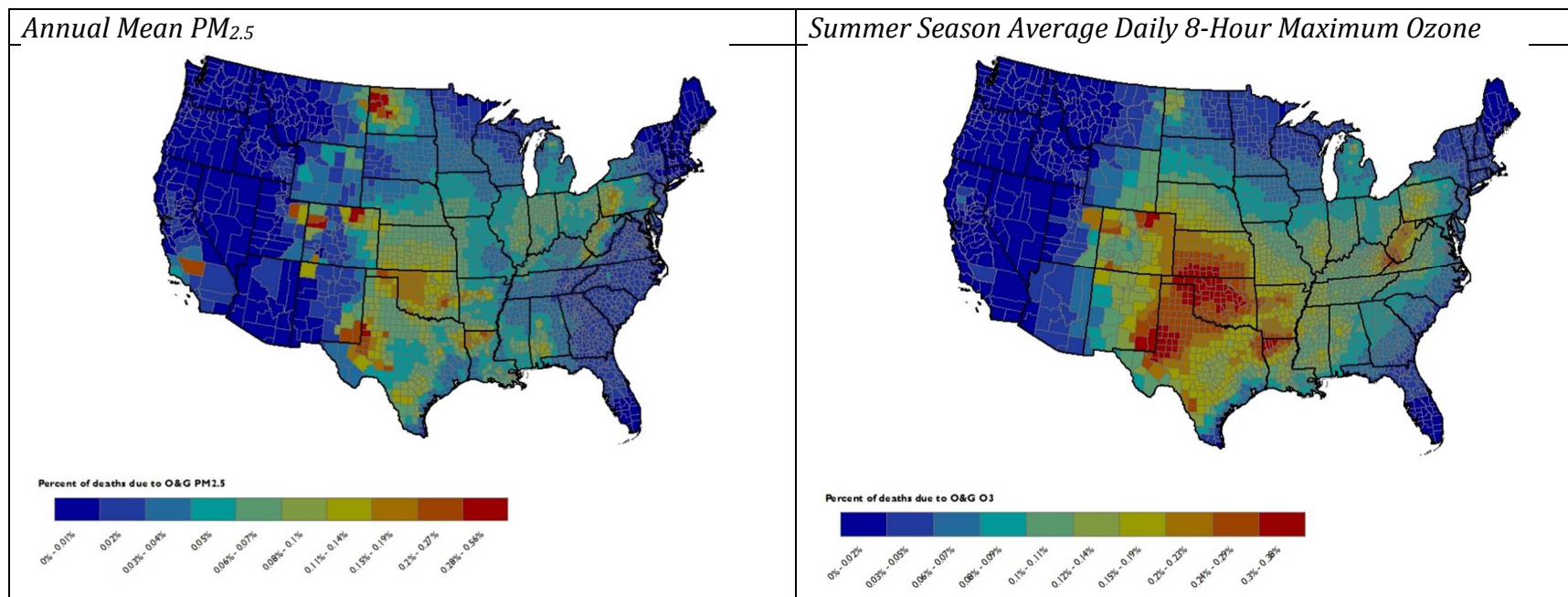report them here as calculated.

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**Table S-7: Value of PM$_{2.5}$ and Ozone Related Mortality and Morbidity Outcomes Attributable to the Oil and Gas Sector in 2025 (Millions of 2015$)**

| Endpoint and Pollutant | Incidence (95% confidence interval)[A] |
|---|---|
| Premature Mortality (Sum of Krewski et al. 2009 & Smith et al. 2009) | $13,000 ($1,200—$37,000) |
| Premature Mortality (Sum of Lepeule et al. 2012 & Zanobett & Schwartz 2008) | $28,000 ($2,500—$80,000) |
| Respiratory Hospital Admissions, Ages 0-99 (PM$_{2.5}$ & O$_3$) | $33 ($-9—$71) |
| Cardiovascular Hospital Admissions, Ages 18-99 (PM$_{2.5}$) | $9 ($4—$17) |
| Acute Bronchitis, Ages 8-12 (PM$_{2.5}$) | $1 ($0—$2) |
| Respiratory Emergency Room Visits, Ages 0-99 (PM$_{2.5}$ & O$_3$) | $3 ($0—$9) |
| Asthma Exacerbation, Ages 6-18 (PM$_{2.5}$ & O$_3$) | $61 ($-52—$180) |
| Work Loss Days, Ages 18-64 (PM$_{2.5}$) | $17 ($15—$20) |
| Acute Respiratory Symptoms, Ages 18-64 (PM$_{2.5}$ & O$_3$) | $200 ($81—$360) |
| Upper Respiratory Symptoms, Ages 9-11 (PM$_{2.5}$) | $1 ($0—$2) |
| Lower Respiratory Symptoms, Ages 7-14 (PM$_{2.5}$) | $0.1 ($0.001—$1) |
| Acute Myocardial Infarction, Ages 18-99 (PM$_{2.5}$) | $120 ($19—$300) |
| School Loss Days, Ages 5-17 (O$_3$) | $74 ($26—$160) |

[A] The confidence intervals for some endpoints were quantified by sampling from a distribution that crosses the null; thus, some lower confidence intervals are negative. Rather than setting these to zero, we report them here as calculated.

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**Figure S-1. Percent of Total Deaths Attributable to Annual Mean PM₂.₅ and Summer Season Daily 8-Hour Maximum**



*Annual Mean PM₂.₅*

Percent of deaths due to O&G PM2.5

0%-0.01% | 0.02% | 0.03%-0.04% | 0.05% | 0.06%-0.07% | 0.08%-0.1% | 0.11%-0.4% | 0.15%-0.19% | 0.2%-0.27% | 0.28%-0.56%

*Summer Season Average Daily 8-Hour Maximum Ozone*

Percent of deaths due to O&G O3

0%-0.02% | 0.03%-0.05% | 0.06%-0.07% | 0.08%-0.09% | 0.1%-0.11% | 0.12%-0.14% | 0.15%-0.19% | 0.2%-0.23% | 0.24%-0.29% | 0.3%-0.38%

**Ozone From the Oil and Gas Sector in 2025**